HIDDEN-INSECT DETECTION BY INFRARED CARBON DIOXIDE GAS ANALYSIS

Principles of System Design

ARS-S-85
March 1976

AGRICULTURAL RESEARCH SERVICE • U.S. DEPARTMENT OF AGRICULTURE

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Principles of System Design

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ABSTRACT

A system for detecting insect infestations in agricultural commodities by infrared carbon dioxide (CO_2) gas analysis is described. The system uses a commercially available Luft CO_2 gas analyzer in intermittent-flow mode to detect insect-produced CO_2 even in the presence of normal atmospheric CO_2. Testing is uncomplicated, quick, and nondestructive of commodity sample and insects, and it produces no byproducts or residues. The method is applicable to a wide variety of materials, either packaged or bulk. It is not limited to insects, but is adaptable to any CO_2-producing organism. Both qualitative and quantitative design considerations are discussed.

INTRODUCTION

The detection of hidden insects in commodities is important in agricultural inspections made for quality control, quarantine, and other purposes. The approaches to detection have embodied a number of physical or chemical principles, including X-rays (*5*),[2] chemical reactions (*3*), electrical properties (*7*), sound (*1*), and nuclear magnetic resonance (*6*). None of these is an ideal detection method, which should be nondestructive, economically feasible, sufficiently rapid to incorporate into existing inspection routines, and reliable over a wide range of environmental conditions.

Detection techniques may be divided into two broad categories: active and passive. Active techniques use external inputs, either physical or chemical, to derive information in the form of an output such as a film image or color change in an indicator material, or an electronically measurable change in resistance, complex impedance, proton spin, or the like. Passive techniques do not use external inputs. Rather, they depend solely on naturally occurring outputs such as infrared energy radiated by the insects, sounds produced by insect feeding, or an aromatic vapor or gas produced by insect metabolism or respiration. Active techniques, such as those using X-rays or chemical reagents, although generally reliable, have some potential for generating personnel hazards or environmental pollution, or for altering or destroying the sample under test. Passive techniques, on the other hand, simply monitor an insect-produced output. Sound monitoring is in this category. However, it has inherent disadvantages since not all life stages of insects produce detectable sounds, temperature extremes may render insects temporarily inactive, commodity sample size may be limited, and coupling of sound energy between insect and detector is virtually impossible with certain commodities.

We favor passive detection and have continued efforts to develop a method relying on insect-produced natural output. It has long been known that insects respire carbon dioxide (CO_2). Instrumentation for CO_2 detection in parts-per-million concentrations is well developed and relatively inexpensive. The concept of using insect-produced CO_2 as an indicator of insect presence is attractive but complicated by CO_2 in the air, comprising about 0.03%. A general description of a sys-

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[2]Italic numbers in parentheses refer to items in "Literature Cited" at the end of this publication.

tem that utilizes this concept and takes into account naturally occurring CO_2 in air has been published (*2*). We now provide a more detailed description of the design principles involved and a discussion of approaches to optimizing system parameters for particular applications.

DESIGN GOALS

Insects of economic and health importance may produce CO_2 at rates as low as 1 microliter per insect per minute, or in a liter of atmosphere, as little as 1 part per million per minute. Thus, a practical device must detect 1 to 2 parts per million of insect-produced CO_2 in the presence of 300 parts per million (0.03%) natural atmospheric CO_2 in a reasonable time, e.g., 1 or 2 minutes. Such detection can be accomplished by a bolus-activated, Luft infrared (IR) CO_2 analyzer with a flow-through reference cell that eliminates the natural atmospheric CO_2 response, thus making differential detection of insect-produced CO_2 possible. Figure 1 shows the functional arrangement of the essential components of this detection system.

We used positive pressure, with bottled air as the carrier gas, to push air through the system. Although negative pressure could be used, with a vacuum pump pulling atmospheric air through the system, excessive fluctuations in ambient CO_2 concentration cannot be tolerated. Such variations will be difficult to avoid if the workspace is confined and workers are near the air intake. Using the negative-pressure approach in a small laboratory room required a CO_2 trap in the air intake line to stabilize the system. Even with these precautions, the system was very sensitive to leaks, such as caused by a faulty gasket on the commodity test chamber, which caused unacceptable drift in the system. The advantages of a positive-pressure system using a stable source of bottled air appear to outweigh a negative-pressure system operated in this particular configuration. However, other configurations may be more suitable for negative-pressure operation and should be considered when adapting the system to a particular application.

Note that the commodity test chamber is outside the analyzer, but interposed between the analyzer

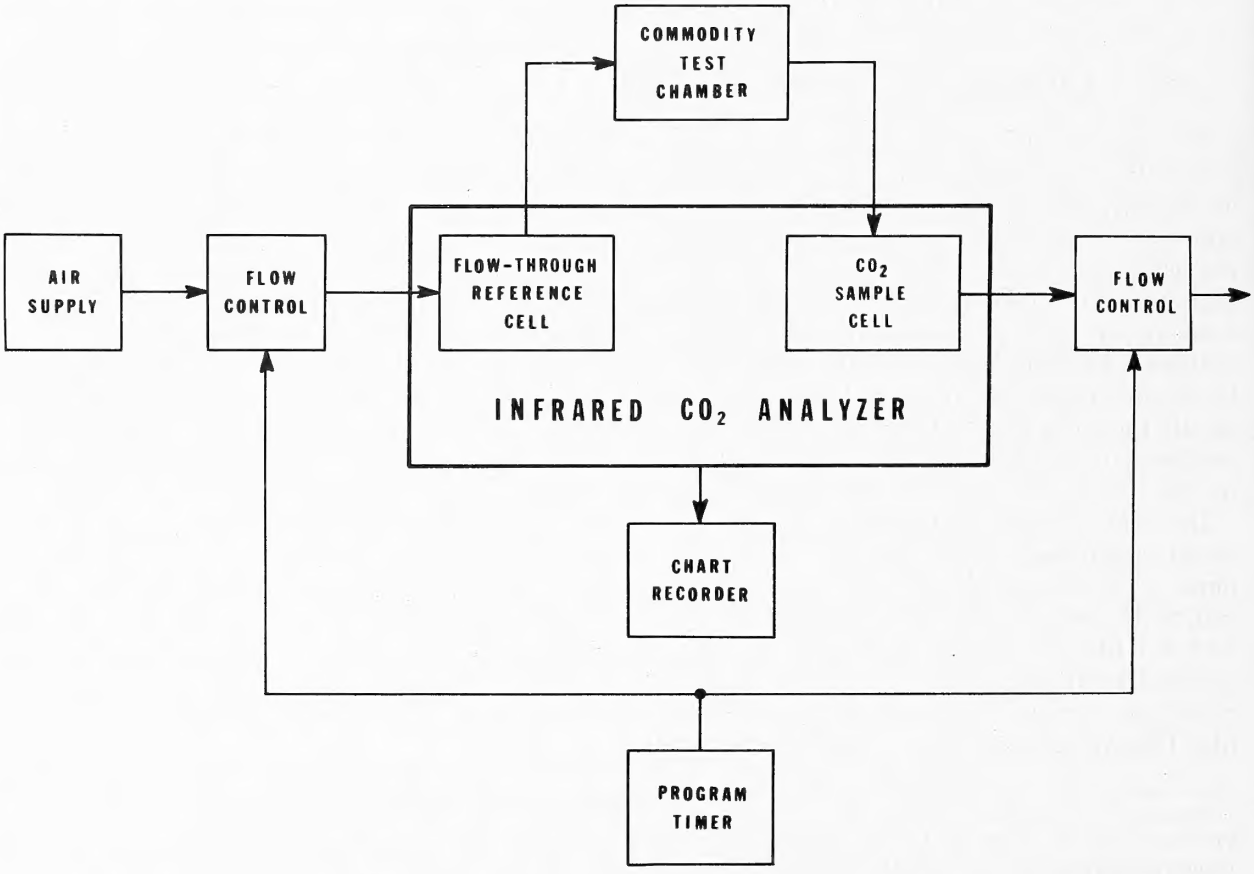

FIGURE 1.—Insect detection system components.

reference and CO_2 sample cells with respect to flow. The carrier gas flows first through the reference cell, thence through the external commodity test chamber, and back through the CO_2 sample cell. Any CO_2 added by the commodity is detected as a concentration difference between the reference and CO_2 sample cells.

We selected intermittent gas flow—flow-stop-hold-purge—instead of continuous flow for several reasons. Our goal was the detection of a very light infestation, even one insect. To do so with continuous flow would require a very low flow rate of the carrier gas to enable the added insect CO_2 concentration to reach a detectable level. This concentration is described by

$$C_n = S_m/Q \ , \qquad (1)$$

where C_n = equilibrium concentration of CO_2 (parts per million),
S_m = source strength of CO_2-producing insects (microliters per minute),
and Q = carrier gas flow (liters per minute).

For very small values of S_m, Q must be low enough for C_n to become detectable. However, with low flow rates the velocity of the gas through the system is low, requiring excessive time to detect any significant CO_2 increase. Under such conditions we have found that insect CO_2 shows up as a slow upward drift of the recorder baseline over a time span of many minutes and is difficult to relate to insect presence. By contrast, intermittent flow yields easily interpretable data quickly and uses less carrier gas.

SYSTEM OPERATION

The insect detection system uses four sequential operations: (1) Test chamber purge, (2) system purge, (3) commodity testing, and (4) signal readout.

Commodity Test Chamber Purge

This purge flushes accumulated gasses out of a commodity-filled test chamber just prior to its connection to the detection apparatus. If a commodity sample of unknown quality has remained in the test chamber for any length of time, it may contain CO_2 from insects in the sample or from slow respiration of the sample itself—particularly samples containing much moisture. Thus, the purge simply flushes out any accumulated CO_2 and reduces the on-line equilibration time required during the next step, system purge. In actual practice, this operation can be arranged so that one sample is being tested while the next sample is being purged.

System Purge

The system uses interrupted gas flow to detect deviation from a CO_2 equilibrium baseline. This baseline is established during system purge. Immediately after the commodity test chamber is connected to the system, the carrier gas is allowed to flow until the differential output from the CO_2 analyzer stabilizes, indicating equilibrium, generally near zero, except in the case of heavy infestations, as discussed later.

Commodity Testing

During this step carrier gas flow is cut off, and the system is sealed by inline valves to permit buildup of insect-produced CO_2 within the sample test chamber. At the onset of the commodity-testing interval, the reference cell, the commodity test chamber, and the CO_2 sample cell contain equal concentrations of CO_2 since equilibrium has been reached during the preceding system purge.

As soon as carrier gas flow ceases, the following events occur if the commodity sample contains insects: in the reference cell, the nominal CO_2 concentration remains essentially constant since the carrier gas is trapped and nonflowing. In the commodity test chamber, the CO_2 concentration begins to rise above the equilibrium value because of the addition of insect-produced CO_2. In the CO_2 sample cell, a condition similar to that in the reference cell exists—the trapped carrier gas is nonflowing and has the equilibrium concentration of CO_2 reached during system purge.

Since there is no flow, any diffusion of CO_2 beyond the commodity test chamber should occur in both directions and, because of system symmetry, produce minimal differential imbalance between the reference and CO_2 sample cells. No discernible imbalance caused by CO_2 diffusion has been observed in the prototype system. However, should it occur, it could be eliminated simply by adding additional valves on each side of the commodity test chamber.

Signal Readout

The valves are opened, unsealing the system, and gas flow is restarted. The higher concentration bolus of CO_2 moves out of the commodity test chamber and through the CO_2 sample cell of the IR analyzer. The resulting imbalance between the two

optical cells of the IR analyzer generates a signal that appears as a peak on the recorder chart. After the bolus has passed through the system, equilibrium of CO_2 concentration is again reached among the reference cell, commodity test chamber, and the CO_2 sample cell. As soon as equilibrium is reached, commodity testing may be repeated as desired.

QUANTITATION OF SYSTEM OPERATIONS

Commodity Test Chamber Purge

Flushing of the sample occurs according to the exponential dilution-ventilation expression

$$C_t = C_0 \exp(-Q_f t / V_s), \quad (2)$$

where C_t = CO_2 concentration (parts per million) at the end of purge time t,
C_0 = initial CO_2 concentration (parts per million),
exp = natural log to base 2.718,
Q_f = flushing flow rate (liters per minute),
t = time (minutes),
and V_s = commodity test chamber air volume (liters).

The air volume in the commodity test chamber will depend on chamber size, geometry, and fullness. The volume will also depend on the particular commodity being inspected, since interstitial "dead air" space varies from commodity to commodity —for example, 35% for soybeans, 37% for grain sorghum, 40% for wheat and shelled corn, 46%–50% for rice, and 47%–55% for oats. More complete listings of commodities and their interstitial volumes are available in the literature (*4*, *8*).

Figure 2 shows a wheat-filled commodity test chamber used in the prototype system. It is a plastic container with sidearm hose fittings. A retaining sieve just above the inlet port near the bottom prevents tube blockage or sample bypassing and presents a uniform circular surface to the inflowing carrier gas. The commodity test chamber is filled to a level just below the exit port, leaving headspace approximately equal to footspace, about 50 milliliters each. The nominal sample volume is 500 milliliters. Since this wheat has about 46% interstitial volume, the 230 milliliters of air ($0.46 \times 500 = 230$) within the wheat must be considered in calculating the net air volume in the commodity test chamber. In this example the total volume is $50+50+230=330$ milliliters of air space.

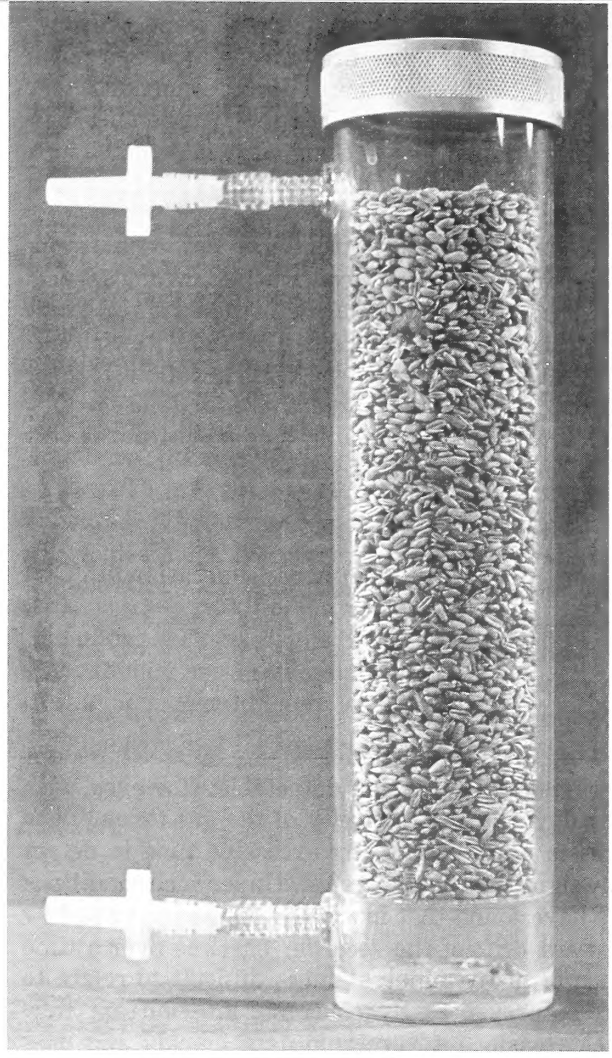

FIGURE 2.—Wheat-filled commodity test chamber used in prototype system.

Generally, the initial CO_2 concentration, C_0, would be unknown. However, the objective of the test chamber purge is simply to lower C_0 significantly so that it can be lowered to equilibrium in a shorter time after being connected to the insect detection system. The rate of reduction can be estimated by examining the timed value of exponent $(-Q_f t/V_s)$ in table 1. The concentration would be reduced as shown in figure 3, curve a.

If a source of CO_2 generation is present and of sufficient magnitude, then the C_t in equation 2 and table 1 will not approach zero as a limit, but will approach equilibrium at a value C_n, or nominal concentration, as shown by curve b in figure 3. (Except in the case of extremely heavy infestations, CO_2 equilibrium should approach zero since the flow rate

TABLE 1.—CO_2 *purge rates for timed values of the exponent* $(-Q_f t/V_s)$ *from equation 2*

$(-Q_f t/V_s)$	C_t/C_0	Remarks
1	0.368	
2	.135	
3	.05	
4	.018	
4.6	.01	100-fold reduction (1% remaining).
9.2	.001	1,000-fold reduction.
13.8	.0001	10,000-fold reduction.

is deliberately set high enough to flush completely any insect CO_2 that may be present in the commodity sample.) C_n is determined by

$$C_n = S_m/Q_f \,, \qquad (3)$$

where S_m = source strength (liters per minute, or microliters per minute $\times 10^{-6}$),
and Q_f = flushing flow rate (liters per minute).

It is apparent that if Q_f is much greater than S_m, then C_n becomes very small, approaching zero as a limit, and can be neglected. This is accomplished by selecting Q_f to be much greater than any anticipated S_m. (This may *not* be the case during system purge or readout since sampling flow rate Q_s in the analyzer is limited by the pressure that the analyzer can withstand and will generally be much lower than flow rate Q_f during commodity test chamber purge, accomplished outside the insect detection system.)

System Purge

Purging of the system follows an exponential dilution expression similar to that described for commodity test chamber purge:

$$C_t = C_0 \exp(-Q_s t/V_s) \,, \qquad (4)$$

where Q_s = system flow rate (liters per minute),
and V_s = net air volume (liters) of commodity test chamber.

The initial concentration C_0 is the equilibrium value reached at the end of commodity test chamber purge (ideally near zero) plus any CO_2 that may have been generated between commodity test chamber purge and system purge. Note that flow rate Q_s is now the system flow rate and, as mentioned above, it will generally be lower than Q_f, the flow rate during commodity test chamber purge.

Also, since Q_s now has a much lower value, nominal concentration C_n obtained at equilibrium may no longer be ignored, *depending on the level of infestation*. With very heavy infestations, S_m may overwhelm the system Q_s so that C_n can never reach equilibrium, or the final equilibrium value of C_n may be so high that it is off the recorder scale. In an inspection, either condition would obviate the need for further testing, since insect presence would have been proved. Selection of as high a Q_s as practical is indicated. This value is limited by the supply capability of carrier gas (where bottled air is used) as well as maximum allowable system pressure.

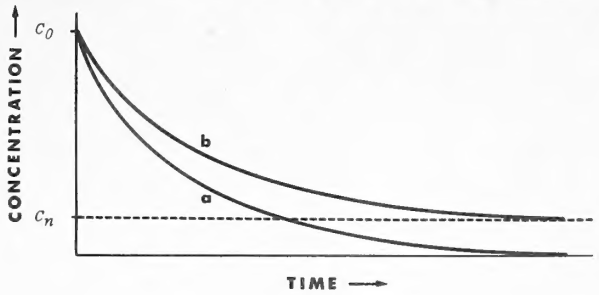

FIGURE 3.—Reduction of CO_2 concentration during commodity test chamber purge.

Figure 4 shows representative CO_2 concentration curves and their relationship to recorder range for a variety of sample conditions.

Commodity Testing

At the end of system purge, carrier gas flow is stopped, and the system is sealed. If insects are in the commodity test chamber, CO_2 will begin to build up linearly with respect to time.[3] The CO_2 concentration will increase according to

$$C_t = (S_m t/V_s) + C_n \,, \qquad (5)$$

where C_t = CO_2 concentration (parts per million) at end of buildup time t (minutes),
S_m = source strength (microliters per minute),
V_s = net air volume in commodity test chamber (liters),
and C_n = nominal CO_2 concentration (parts per million), if any, remaining at end of system purge.

[3]Many variables can affect the CO_2 generation rate of insects, including commodity sample handling, radical changes in environment, temperature, life stage, etc. However, if rough handling and drastic changes are avoided, essentially constant CO_2 yield should be obtained during the short time it would take to make a test. In tests with the prototype, peak heights from the same infested commodity sample varied about ± 5% over 90 minutes, certainly much longer than an actual inspection test would take.

This expression illustrates the important relationship between interstitial commodity volume and net air volume in the commodity sample test chamber. The ratio of S_m to V_s will in large part determine the time required to bring C_t up to a level detectable by the analyzer. With insect source strengths in microliters per minute, the smaller the V_s the greater will be the increase in CO_2 concentration in a given time. If a commodity test chamber is only partly filled with solids, leaving much headspace, insects will have to produce CO_2 much longer to bring the concentration up to a detectable level than they would in a totally filled chamber. Similarly, a commodity containing large interstitial voids would require a longer testing time than would a commodity having small interstitial voids.

Thus, the time required for commodity testing will be determined by insect CO_2 source strength, analyzer sensitivity, and net air volume in the commodity test chamber, which in turn depends on commodity interstitial volume. A limiting factor in testing time is respiration of the test commodity itself, especially under high-moisture-content conditions in which CO_2-producing molds or fungi may also be present. Another limiting factor is the time per test allowed under an inspection procedure.

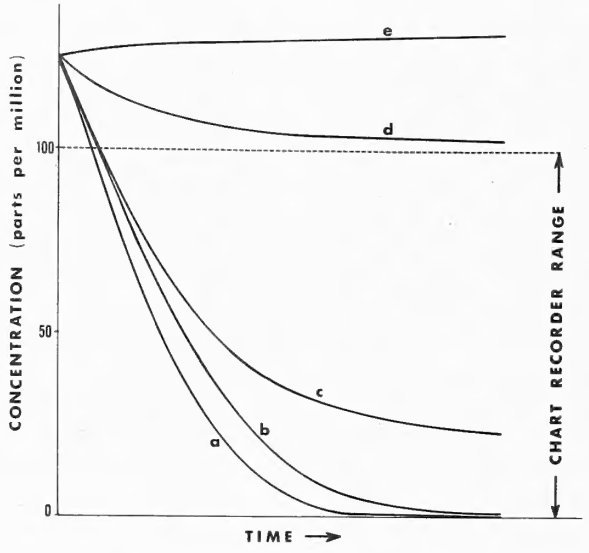

FIGURE 4.—Reduction of CO_2 concentration during system purge. (a) Uninfested sample, rapid purge to zero concentration. (b) Lightly infested, purge to nearly zero or very low C_n. (c) Heavily infested, purge to stable moderate value of C_n. (d) Extremely infested, equilibrium value of C_n lies beyond recorder range. (e) Extremely infested, flow rate of carrier gas too low to purge insect-produced CO_2, the concentration of which increases indefinitely beyond recorder range.

Figure 5 shows the building of CO_2 in the commodity test chamber for a variety of test conditions.

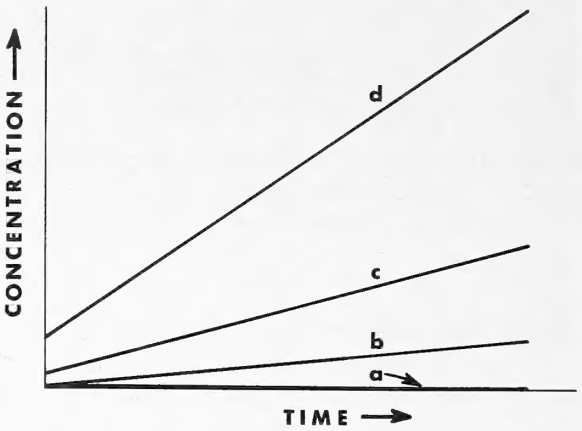

FIGURE 5.—Buildup of CO_2 during commodity testing. (a) Uninfested commodity, no buildup of CO_2. (b) Lightly infested, slight buildup of CO_2. (c) Moderately infested and (d) heavily infested, showing buildup to increasingly higher values of CO_2 concentration during commodity-testing interval.

Signal Readout

After a suitable commodity-testing interval, the carrier gas flow is restarted. The inflow of carrier gas causes exponential dilution of the CO_2 within the commodity test chamber. Downstream in the CO_2 sample cell, the CO_2 builds up exponentially to a peak concentration and then decays exponentially to the equilibrium value. The characteristics of the bolus, as sensed in the analyzer CO_2 sample cell, are determined by the dilution-ventilation equations for exponential buildup and decay, presented below. These equations can be used to predict system behavior within various parameters.

Characterization of the bolus may be simplified by assuming zero path distance between the commodity test chamber and the analyzer CO_2 sample cell. Consider the two enclosures to be contiguous, with a connecting aperture as shown in figure 6. Let a represent the commodity test chamber and b the CO_2 sample cell in the IR analyzer. In a,

$$C_{t_a}=C_{\max}\exp\left(-Q_s t/V_a\right), \qquad (6)$$

and in b,

$$C_{t_b} = C_{t_a}[1 - \exp(-Q_s t/V_b)], \quad (7)$$

where C_{t_a} = CO_2 concentration (parts per million) in chamber a at time t,
C_{max} = CO_2 concentration (parts per million) in chamber a at end of commodity-testing interval (just prior to restart of carrier gas flow),
Q_s = carrier gas flow rate (liters per minute),
V_a = net air volume in commodity test chamber (liters),
t = time (minutes) after restart of carrier gas flow,
C_{t_b} = concentration (parts per million) in cell b at time t,
and V_b = volume of analyzer CO_2 sample cell (liters).

The gas flowing through the connecting aperture will have the CO_2 concentration of chamber a (equation 6) as it enters into the buildup of concentration (equation 7) in detector cell b. The factor C_{t_a} in equation 7 is a variable and is equal to equation 6. Substituting equation 6 into equation 7 gives

$$C_{t_b} = [C_{max} \exp(-Q_s t/V_a)][1 - \exp(-Q_s t/V_b)]. \quad (8)$$

In a real system the tubing connecting the commodity test chamber and the analyzer CO_2 sample cell has a finite volume. This volume causes some deviation in system behavior from that predicted by the model. However, we observed a reasonable match between the theoretical and actual peaks in our tests of the prototype.

OPTIMIZING SYSTEM OPERATION

The design of an insect detection system using infrared CO_2 analysis should take into consideration the factors that can be manipulated to provide the best system response. Commercially available analyzers have not been designed for the present application, and they have generally been designed for continuous-flow analysis. Insect detection that requires a system capable of detecting a single insect in a fair quantity of commodity or in a short time interval will admittedly push the analyzer to its sensitivity limits. When crowding these limits, certain factors that might normally be ignored will become important and must be dealt with to prevent degradation of overall system performance. Such factors will include noise, carrier gas pressure surges, commodity respiration, and commodity test chamber design.

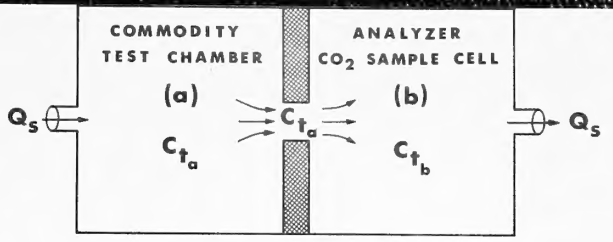

FIGURE 6.—Mathematical relationship of CO_2 concentrations in commodity test chamber and analyzer CO_2 sample cell.

Noise

Two sources of noise must be dealt with when operating the IR analyzer at high sensitivity ranges: internal system noise and external electrical interference.

System noise.—In a well-designed commercial Luft IR CO_2 analyzer, the internal noise will likely be reasonably low. Restriction of system bandwidth by electronic filters is limited by the data-handling rate required in the chopper-demodulator system generally used. At very high sensitivity levels some chopper frequency "waving" of the recorder baseline will be observed. Although this can be removed by a low pass filter between analyzer and recorder, the presence of this noise serves as a good check on overall system sensitivity.

Electrical noise.—Electrical transients may be caused by timer and solenoid valve switching. These can be controlled with good equipment design, using proper shielding and electrical filters as required.

Air Pressure

Some IR analyzers are sensitive to air-pressure transients. Intermittent flow, as used in this system, can produce transients that will appear on the recorder chart. Such transient peaks are easily recognized, however, since they show up as short-duration "spikes" bearing little similarity to the longer insect-produced peaks. Significant "pressure spiking" should nonetheless be corrected during instrument development, since it may mask marginally detectable insect CO_2 signals and thus confuse interpretation. In our prototype the desiccators

used for moisture protection "softened" pressure transients to an insignificant level. However, other transient-damping methods may have advantages. As mentioned before, the bolus is degraded by increased system volume, and any damping should therefore be accomplished with minimum addition to system volume.

Commodity Sample Respiration

Grain with high moisture content can respire significant amounts of background CO_2. This will obscure insect-produced CO_2 and set an absolute limit to detection capability. A compromise will be necessary between maximum allowable moisture content and minimum detectable insect levels.

Because the bolus concentration is a linear function of commodity-testing time, the bolus concentration could be amplified indefinitely by increasing the testing interval, if the test involved an inert commodity. However, if the commodity itself generates CO_2, practical limitations will be encountered in optimizing insect-detection capability. Also, mold and fungus respiration will have to be considered.

Optimizing the CO_2 Bolus

Since the concentration of the bolus CO_2 is an inverse function of system volume, the interstitial volume, commodity test chamber headspace volume, and the volume of system plumbing should be held to the minimum possible values. This can be accomplished by proper design of the test chamber and the use of minimum lengths of connecting tubing.

Commodity Test Chamber Design

Considerable potential exists in the design of the commodity test chamber. We used 500-milliliter plastic Drierite desiccator containers and also successfully tried plastic and glass jars, boxes, vials, and bags. For bulk commodities, chamber geometry appears to be unimportant if the container is filled, has minimum headspace, and has good gas flow-through characteristics. The test chamber should be tailored to reasonably fit packaged products. For odd-shaped packages or objects some variation of plastic shrink packaging might be considered. Another approach would be negative air pressure (vacuum) in the system, with a flexible jacket or bag as the commodity test chamber. The system vacuum could be used to collapse the jacket into intimate contact with the commodity package, thus minimizing dead-air space in the commodity chamber. However, as discussed under "Design Goals," the disadvantages of a negative-pressure system must be considered and adequate design precautions taken.

Carrier Gas Flow Rate

The peak amplitude of the CO_2 bolus is independent of carrier gas flow rate. The *area* under a peak does vary significantly with carrier gas flow rate, but the peak *amplitude* remains constant. Low flow rates broaden the peak, while high flow rates narrow the peak and make it more readily identifiable as insect related. High flow rates also transport the bolus through the system in proportionately shorter times, thus shortening sample inspection time. Therefore, the maximum flow rate consistent with the pressure capabilities of the IR analyzer windows and the permissible consumption rate of carrier gas, if bottled air is used, should be used.

Figure 7 shows the relationship between the net air volume of the commodity test chamber (related to commodity and sample size) and the sample cell volume (related to required detector sensitivity). For maximum bolus concentration yield in the shortest time, the ratio of commodity test chamber volume to CO_2 sample cell volume should be as high as possible. The sample cell volume is determined by the manufacturer for a given instrument sensitivity.

Interrelationship of System Variables

The interrelationships among system variables are shown in figure 8. For a given insect species

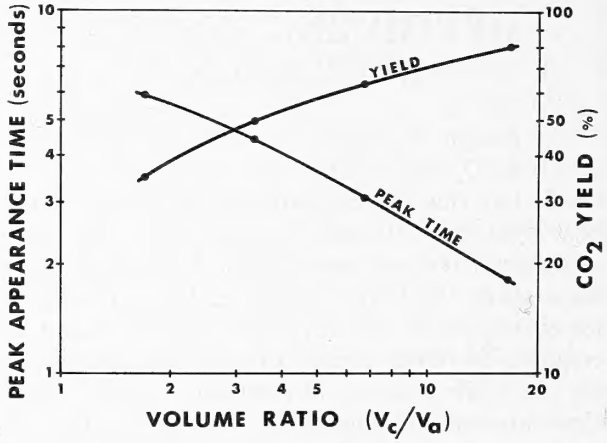

FIGURE 7.—Bolus yield as a function of commodity test chamber and analyzer CO_2 sample cell volume ratios.

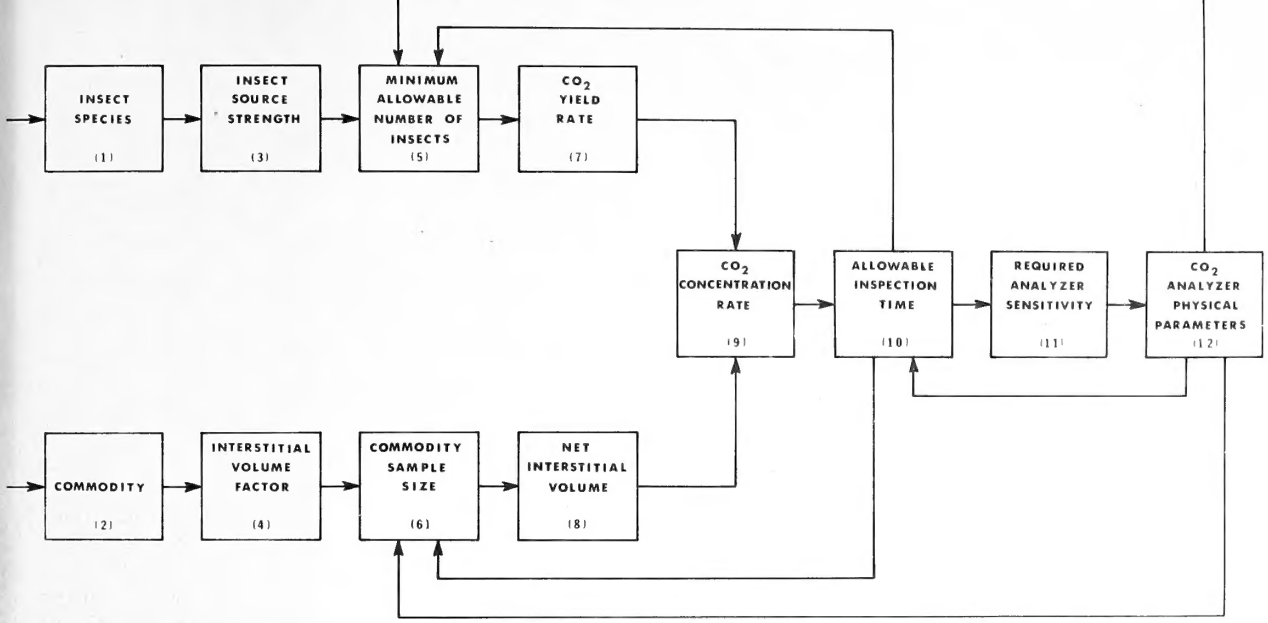

FIGURE 8.—Interrelationships among system variables.

and a given commodity, there are constraining relationships among minimum allowable number of insects, desired commodity sample size, allowable inspection time, and required analyzer sensitivity. Tradeoffs must be made among these constraints to achieve optimum system operation for a particular application. An example of the use of figure 8 is given below:

GIVEN:

(1) Insect species (e.g., rice weevil).

(2) Commodity sample (e.g., wheat).

DEPENDENT:

(3) Insect source strength (e.g., 1.5 microliters CO_2 per insect per minute), dependent on 1.

(4) Interstitial volume factor (e.g., 0.46 for wheat), dependent on 2.

DESIRED:

(5) Minimum allowable number of insects in commodity sample. This is a quality standard, and implies that the minimum allowable number must be detectable.

(6) Commodity sample size (e.g., 1,000 grams). This is the size of the random sample taken from the larger bulk commodity. The sample may be used for purposes other than insect inspection—moisture content, foreign matter, etc. For a given sample *weight* and commodity *density*, a certain commodity test chamber *volume* is required.

DEPENDENT:

(7) The CO_2 yield rate depends on 1, 3, and 5.

(8) The net interstitial volume depends on 2, 4, and 6.

(9) The CO_2 concentration rate is determined by the combination of 7 and 8.

DESIRED:

(10) Allowable inspection time. Preferably the shortest practical time, but definitely limited to a minimum determined by 5 and 6.

DEPENDENT:

(11) Required analyzer sensitivity. The concentration rate, 9, and the allowable inspection time, 10, combine to demand a certain analyzer sensitivity.

(12) Once the analyzer sensitivity, 11, is determined, the IR analyzer design fixes the CO_2 detector cell volume.

Ultimately, there must be a compromise between (5) minimum allowable insects, (6) commodity sample size, and (10) allowable inspection time, as determined by the state-of-the-art technology in the CO_2 IR analyzers available. A final limit is imposed by elevated moisture contents that cause significant grain respiration. This limit must be determined for a particular commodity, and moisture determination must precede inspection for insect infestation to determine whether this limit has been exceeded.

CONCLUSIONS

CO_2 analysis appears to be a practical insect-detection method that can be readily adapted to a broad range of commodities and inspection requirements. The system designer has a great deal of latitude in choosing system components and their mode of operation. Gas analyzer technology and infrared hardware continue to improve and advantage can be taken of advances in these fields.

Numerous areas for further development and application should be explored. The system is not limited to insect applications, but is adaptable to the detection of many CO_2-producing organisms. The authors will be pleased to give assistance in developing concepts for further applications.

LITERATURE CITED

(1) Adams, R. E., Wolfe, J. E., Milner, Max, and Shellenberger, J. A. 1953. Aural detection of grain infested internally with insects. Science 118(3057): 163–164.

(2) Bruce, W. A., and Street, M. W. 1974. Infrared CO_2 detection of hidden insects. J. Ga. Entomol. Soc. 9(4): 260–265.

(3) Dennis, N. M., and Decker, R. W. 1962. A method and machine for detecting living internal insect infestation in wheat. J. Econ. Entomol. 55(2): 199–203.

(4) Gustafson, R. J., and Hall, G. E. 1972. Density and porosity changes of shelled corn during drying. Trans. ASAE (Am. Soc. Agric. Eng.) 15(3): 523–525.

(5) Milner, Max, Lee, M. R., and Katz, R. 1950. Application of X-ray technique to the detection of internal insect infestation of grain. J. Econ. Entomol. 43(6): 933–935.

(6) Street, M. W. 1971. Nuclear magnetic resonance for detecting hidden insect infestation in stored grains. J. Ga. Entomol. Soc. 6(4): 249–254.

(7) Wirtz, L. A., and Shellenberger, J. A. 1963. A rapid method to determine insect infestation in grain using electricity. Cereal Sci. Today 8(9): 305–318.

(8) Zink, F. J. 1935. Specific gravity and air space of grains and seeds. Agric. Eng. 16(11): 439–440.

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